

STEP VOLTAGE ANALYSIS FOR THE CATENOID LIGHTNING PROTECTION SYSTEM

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ABSTRACT

The main objective of the Aerospace Corporation-proposed overhead Catenoid Lightning Protection System (CLPS) is personnel safety. To ensure working personnel's safety in lightning situations, it is necessary that the potential difference developed across a distance equal to a person's pace ('step voltage') does not exceed a separately established 'safe voltage' in order to avoid electrocution (ventricular fibrillation) of humans. Therefore the first stage of the analytical effort is to calculate the open-circuit step voltage. In this paper we develop an impedance model for this purpose, which takes into consideration the earth's complex impedance behavior and the transient nature of the lightning phenomenon. In the low frequency limit, this impedance model is shown to reduce to results similar to those predicted by the conventional resistor model in a DC analysis.

INTRODUCTION

Lightning presents a major recurring concern in space launch operations. Today's space launch requires a great deal of preparation, and any delay of launches due to adverse weather conditions, such as lightning, would result in considerable schedule and cost impact. For example, Range Safety requires that personnel be evacuated when a possible lightning storm is expected to occur within five nautical miles (9.25 km) of the launch complex when solid propellants are present. The result is, among other things, a significant loss of man-hours and many delayed launches. While all hazards from lightning cannot be completely eliminated, it is a fact that a system and working personnel can be made relatively immune to lightning effects by well-planned protection schemes. The Aerospace Corporation-proposed overhead Catenoid Lightning Protection System (CLPS)¹ as shown in Figure 1, which is designed to divide and divert lightning currents away from the work areas beyond the perimeters of the launch pad, is such an example. Since its main objective is personnel safety, one of the first questions to be answered is: what is the potential difference developed between a person's feet one meter apart (commonly known as the 'step voltage')² within the CLPS umbrella when a direct lightning attachment to the catenary wires or fuel vents occurs? This voltage, when compared to a separately established 'safe step voltage' to avoid ventricular fibrillation (electrocution) in humans, would define a safe zone for working personnel. MIL-STD-419A utilizes a 1000-volt maximum *safe* step voltage for humans in situations such as a lightning environment.

To predict the open-circuit step voltage, a resistor model for the soil is usually used in a DC analysis. In studying ground hazards due to lightning for the CLPS, The Aerospace Corporation first proposed a soil resistor model which consists of two different soil layers each with different resistivities. While this approach is consistent with available literature^{3,4}, it was felt that because of the transient nature of lightning and the complex impedance behavior of the medium (e.g. soil, water, etc.), a transient analysis of the situation, especially when personnel safety is at issue, is necessary. The need for a transient analysis becomes clearer

¹H. Heritage, & H.Z. Wilson, Aerospace Corp., private communications.

²IEEE Guide for Safety in Substation Grounding', IEEE Std 80-1976.

³MIL-HDBK-419A, Volume I, Chapter 2, 29 December, 1987.

⁴A.P. S. Melliopoulos, 'Power System Grounding and Transients', Chapter 5, Marcel Dekker, Inc., 1988.

when the adequacy of the DC analysis for lightning events is re-examined in terms of the skin depth [4] $\delta = \sqrt{2/\mu\omega\sigma}$, where $\mu = 4\pi \times 10^{-7}$ Henry/m is the permeability of the medium, $\omega = 2\pi f$ is the angular frequency of the lightning current, and $\sigma = 1/\rho$ is the conductivity with ρ as the resistivity of the medium. For a DC analysis to be valid, the skin depth has to be large (say, ten times larger) compared to the grounding system (in this case, the ground rod at the end of a catenary wire). For a nominal soil resistivity of $40\Omega \cdot m$ and a lightning frequency of 100kHz, the skin depth is approximately 10 meters which is about the same length as a typical ground rod. Therefore, an approach different from the conventional DC analysis has to be adopted. For this reason we propose to use an impedance model for the media and perform a simplified transient analysis to predict the step voltage.

IMPEDANCES OF MEDIA AND INJECTION CURRENTS

In this paper we propose to model the ground as a two-layer medium with complex impedances (see Figure 2), and compare it with the two-layer resistor (DC) model. The upper layer represents the dry soil and the lower layer consists of the water-saturated earth below. In practice, the length of the ground rod is chosen to ensure that good contact is established with the more conductive lower layer for that location. The frequency dependence of the medium impedance is well known in problems related to electromagnetic wave propagation in media such as soil and water⁵. The intrinsic impedance of a medium for the electromagnetic wave propagation $Z(\omega)$ ⁶ in ohms is given by

$$Z(\omega) = \sqrt{\frac{\mu_o}{\epsilon \left(1 + \frac{\sigma}{j\omega\epsilon}\right)}} \quad (1)$$

where μ_o is the permeability for non-ferromagnetic media such as free space, soil and water, and ϵ for the upper soil layer is taken to be twelve times the free space permittivity [6]. In this analysis the above impedance is assumed for the current wave propagation through the two-layer soil medium. The dependence of $Z(\omega)$ on the upper soil layer depth (L) has been introduced implicitly through the average soil resistivity, for example, at $L = 3$ meters. Based on our measurements of ρ at Launch Complex #41 at Cape Canaveral Air Force Station (LC41/CCAFS)⁷, it is found that the general dependence of ρ on L is difficult to quantify. However, since our measurements show that beyond soil depth $L \sim 3$ meters, ρ has, in general, a value around $\leq 20\Omega \cdot m$ because of saturation with salty underground water, therefore $Z(\omega, L = 3 \text{ meters})$ is chosen in this analysis to illustrate the methodology. The transient source current $i(t)$ due to lightning is taken to be a double exponential waveform⁸, although any other lightning waveforms can also be used:

$$i(t) = i_o \cdot (e^{-\alpha t} - e^{-\beta t}) \quad (2)$$

which has the complex form in the frequency domain by Fourier transformation:

$$I(\omega) = i_o \cdot \left(\frac{1}{\alpha + j\omega} - \frac{1}{\beta + j\omega} \right) \quad (3)$$

where $j = \sqrt{-1}$, α is equal to $1/25$, β is equal to $1/1.5$, time t is in μSec , and i_o is the current amplitude at the ground injection point. In case of a direct lightning attachment to the lightning rod on top of the catenary tower which is deemed to be most probable, the peak lightning current of 255kA is assumed to be equally divided among 10 catenary wires, resulting in a 25.5kA peak current on each catenary wire at the ground injection point. Note that for an asymmetric structure like the proposed Catenoid System, the simplistic way of dividing current equally is not true even for the DC case, let alone in the transient situation where cross couplings and re-radiations among all structures and wires are known to exist. However, as a scoping effort, we feel this current division is a reasonable simplification.

⁵ K.S.H. Lee, Ed., 'EMP Interaction: Principles, Techniques and Reference Data', AFWL-TR-80-402, December 1980.

⁶ Vance, 'Coupling to Shielded Cables', Wiley-Interscience, 1978.

⁷ R. Briët & J.C. Chai, 'Additional Measurement Data on Soil Resistivities at LC41/CCAFS', Aerospace Memo #90(5217-JC)03, January 24, 1990.

⁸ An approximate analytical form for the lightning waveform specified in 'Military Specification, Bonding, Electrical, and Lightning Protection for Aerospace Systems', MIL-B-5087B, 31 August, 1970.

A direct lightning attachment to the existing vent towers protruding outside of the catenary system can also occur, although with lower probability. The injection current at the vent tower will be larger due to fewer dividing wires (e.g. four wires in this case), which will result in a greater potential difference, also because of closer proximities to the work areas.

TRANSIENT ANALYSIS AND STEP VOLTAGES

The potential $E(z)$ due to a current flow I_s at z in a two-layer medium (Figure 2), according to the resistor (DC) model [3 and 4] is given by

$$E(z) = \frac{0.386\rho_s I_s}{L} \cdot \log_{10} \left[\frac{L}{z} + \sqrt{1 + \left(\frac{L}{z}\right)^2} \right] \quad (4)$$

where L is the upper soil layer depth of resistivity ρ_s , and I_s is the DC current flow through the upper soil layer which is explicitly dependent on L and can be found by the proportional DC current relation to ρ 's and L 's of the two soil layers⁹. The step voltage between z meters and $(z + 1)$ meters from the current injection point predicted by the DC model is then

$$V_{DC,step}(z) = E(z) - E(z + 1) \quad (5)$$

In our analysis a simplified approach is adopted to give an estimate of the transient effects. The total ground current $I(\omega, z) = I(\omega)e^{-\gamma(\omega)z}$ at a distance z from the ground injection point is divided, according to the current division rule in the AC circuit analysis, to yield the residual current flowing in the upper layer of soil:

$$I_s(\omega, z) = \frac{Z_w(\omega)}{Z_w(\omega) + Z_s(\omega)} \cdot I(\omega, z) \quad (6)$$

where $Z(\omega)$ is the complex impedance, and subscripts s and w represent upper layer soil and lower layer wet soil, respectively. The propagation constant $\gamma(\omega)$ which contains an attenuation factor and a phase factor is included in the model. The potential difference between a distance of z meters and $(z + 1)$ meters from the current injection point in the surface soil layer, known as the step voltage, then follows directly

$$V_{step}(\omega, z) = [I_s(\omega, z) - I_s(\omega, z + 1)] Z_s(\omega) \quad (7)$$

The Fourier transform of V_{step} to the time domain will yield the waveform of $v_{step}(t, z)$, whose maximum value is then picked as the step voltage for each distance z from the source of injection. For this analysis, the upper soil resistivities, ρ_s , used were 1500 and 100 $\Omega \cdot m$, which represent two typical values for the dry and wet upper soil layers at the launch site, while the lower layer starting at a depth of $L = 3$ meters is less influenced by weather and was taken to be a constant $\rho_w = 20 \Omega \cdot m$. The calculations were repeated for various distances from the current injection point ranging $z = 3$ to 46 meters. The analysis can, of course, be carried out for other layer depths with different resistivities.

RESULTS

The step voltages with catenary wire current injection calculated using the impedance model are shown in Table I, which are also plotted in Figure 3 for easy visualisation. As expected, a more resistive upper soil layer (e.g. $\rho_s = 1500 \Omega \cdot m$ vs. $\rho_s = 100 \Omega \cdot m$) results in a larger step voltage. It shows that in order to keep the step voltage below a fixed voltage, say, one thousand volts, the distance from the injection point should be greater than 41 meters for $\rho_s = 1500 \Omega \cdot m$, while for $\rho_s = 100 \Omega \cdot m$ the distance is 18 meters.

A comparison of the impedance model results (injection by Catenary Wire) with those of the resistor model is shown in Figure 4 for $\rho_s = 100 \Omega \cdot m$. It shows that in order to keep the step voltage below a

⁹H.E. Eley, 'Step Potential with the Overhead Lightning Protection System', Aerospace Memo #3530.HEE.2251I, 9 March, 1990.

fixed voltage, say, one thousand volts, the 'keep-out' distance is only 3.5 meters for $\rho_s = 100\Omega \cdot m$ by the resistor model prediction, while a 18-meter distance is required by the impedance model. However, in order to fairly assess the safety issue for humans in lightning situations, the *human body impedance*¹⁰ and induced human body currents have to be included in the consideration to establish a safety standard. Very little is available in the open literature regarding the current level versus frequency required to produce ventricular fibrillation in humans, although it has been known¹¹ that higher currents can be tolerated at higher frequencies (or shorter durations).

Calculations were also performed for two different current injection scenarios: catenary wire current injection and vent towers (oxidiser vent stack and fuel vent stack) current injections. Table II gives a comparison of the step voltages due to these two different current injection scenarios for the closest points in the work area. For illustration purposes, the work area is assumed to be a 30-meter square at the center of the launch pad (see Figure 1(b), Top View). Of course, there are other areas (e.g., near the vent towers) that may also be designated as work areas which can be considered using the same methodology. It can be seen from Table II that vent tower wire current injections result in much greater step voltages, thus posing greater risks for personnel safety if the lightning is to attach itself to the vent towers which protrude outside the protective region of the proposed catenary system.

Since the step voltage is crucial to personnel safety, a verification of this quantity is of utmost importance. Short of the actual measurements of the step voltage in a lightning environment, the impedance model can be checked to see if it can be reduced, in the *low frequency* limit, to the resistor model, i.e.,

$$\lim_{\omega \rightarrow 0} [V_{step}(Z(\omega))] = V_{DC,soil}(R) \quad (8)$$

where $Z(\omega)$ is the complex impedance and R is the DC resistance of the upper soil. This was accomplished by using 8 kHz as the low frequency cut-off of the impedance model. It was found that at 10 meters and $\rho_s = 100\Omega \cdot m$, the low frequency approximation of the impedance model yields a step voltage of 177 volts, while the resistor model result is 168 volts. This lends some confidence to the analytical validity of the impedance model and the transient analysis.

CONCLUSIONS

The study of step voltage for the CLPS leads to the following observations:

- In comparison to the resistor model, the impedance model predicts:
 - A higher ($\sim 3x$) step voltage at all distances. This could result in a larger 'keep-out' distance; however, the human body response as a function of the lightning frequency needs further investigation in order to establish a safety zone.
 - A similar attenuation of step voltages as the distance increases.
- The vent tower current injection scenario results in greater step voltages, and thus poses greater threat to personnel safety in the assumed work area. Some measures to reduce this threat may need to be addressed.
- At low frequencies, the impedance model can be reduced to yield similar results as the resistor model. This lends some *analytical* credibility to the model and analysis.

¹⁰For example, human body impedance as measured and calculated by A.W. Guy, 'Analysis of Time Domain Induced Current and Total Absorbed Energy in Humans Exposed to EMP Electric Fields', Bioelectromagnetics Research Laboratory, University of Washington, Final Report, June 30, 1989.

¹¹T. Bernstein, 'Effects of Electricity and Lightning on Man and Animals', Journals of Forensic Sciences, Vol. 18, No.1, January 1973, and 'Electrocution and Fires Involving 120/240-V Appliances', IEEE Transactions on Industry Applications, Vol. IA-19, No.2, March/April, 1983.

- It is of utmost importance to ensure personnel safety at launch sites in lightning situations. To fully verify the prediction of step voltages which concerns personnel safety (the major purpose of the CLPS), a well-conducted *dynamic test* in a simulated lightning environment is necessary.

ACKNOWLEDGEMENT

This study was conducted in support of the AF/SSD Titan IV Program. The authors would like to express their appreciation of H. A. Heritage and H.Z. Wilson for the valuable discussions of their design concepts of the catenoid system. Also, thanks are due to the ground supporting crews of the ETR for their help in obtaining the resistivity measurements at LC41/CCAFS.

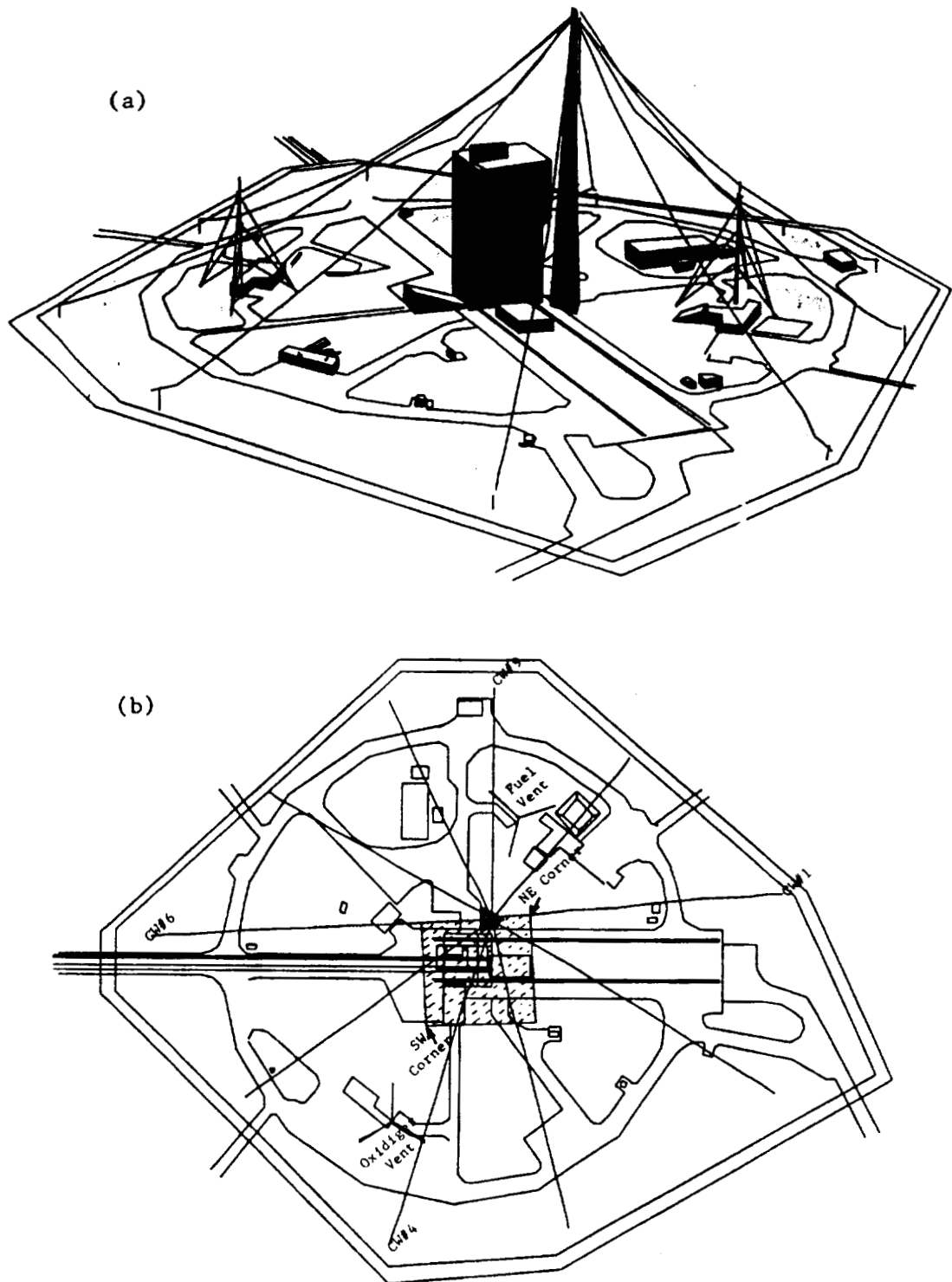


Figure 1. Artist's Rendition of the Overhead Catenoid Lightning Protection System (CLPS) at Launch Complex #41 at Cape Canaveral Air Force Station:
 (a) Slant View. (b) Top View, shaded area is the assumed work pad.

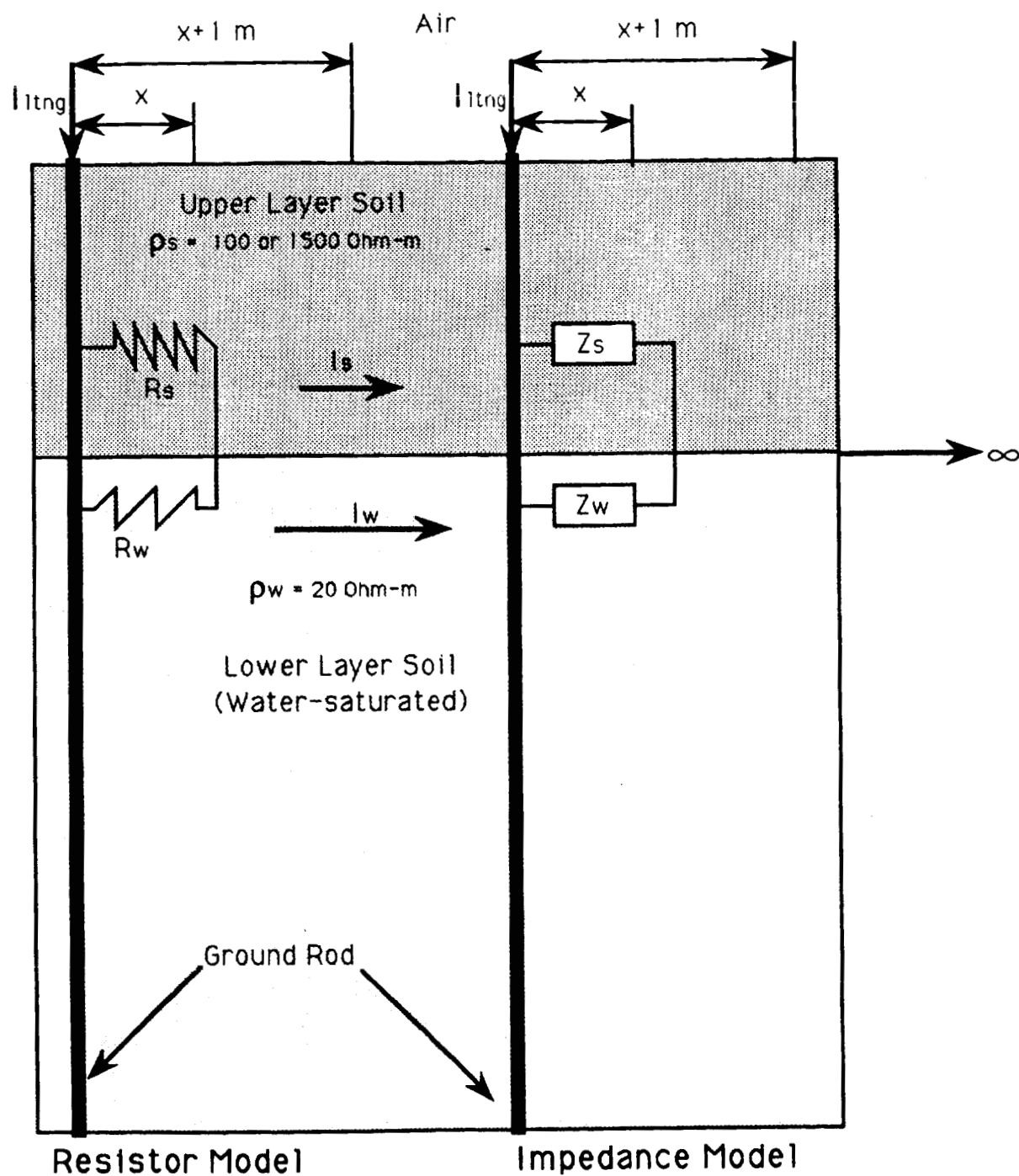


Figure 2. Resistor Model and Impedance Model for the Calculation of Step Voltages.

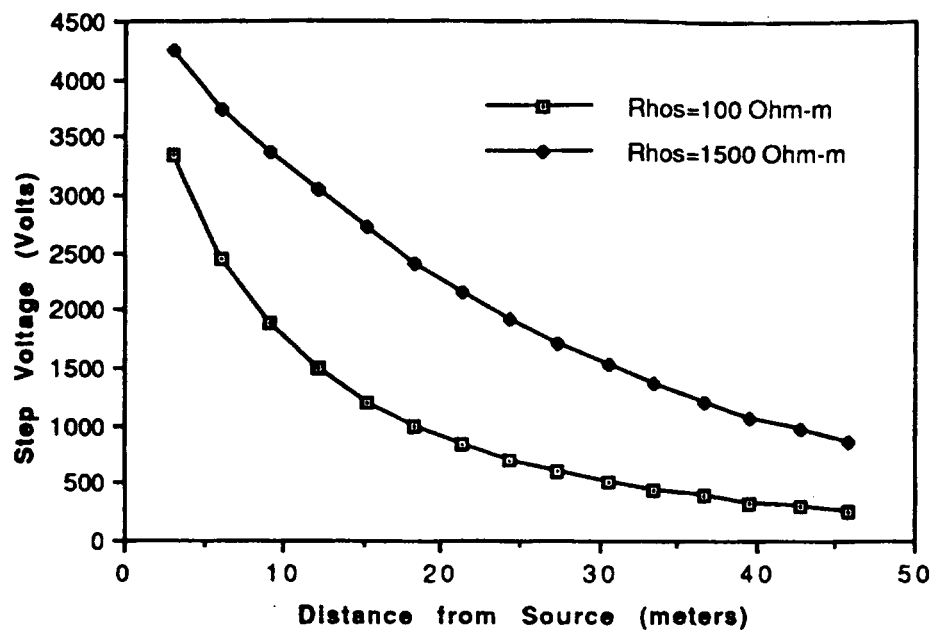


Figure 3. Comparison of Step Voltages by the Impedance Model for Different Upper Soil Resistivities $\rho_s = 1500 \Omega \cdot m$ and $\rho_s = 100 \Omega \cdot m$.

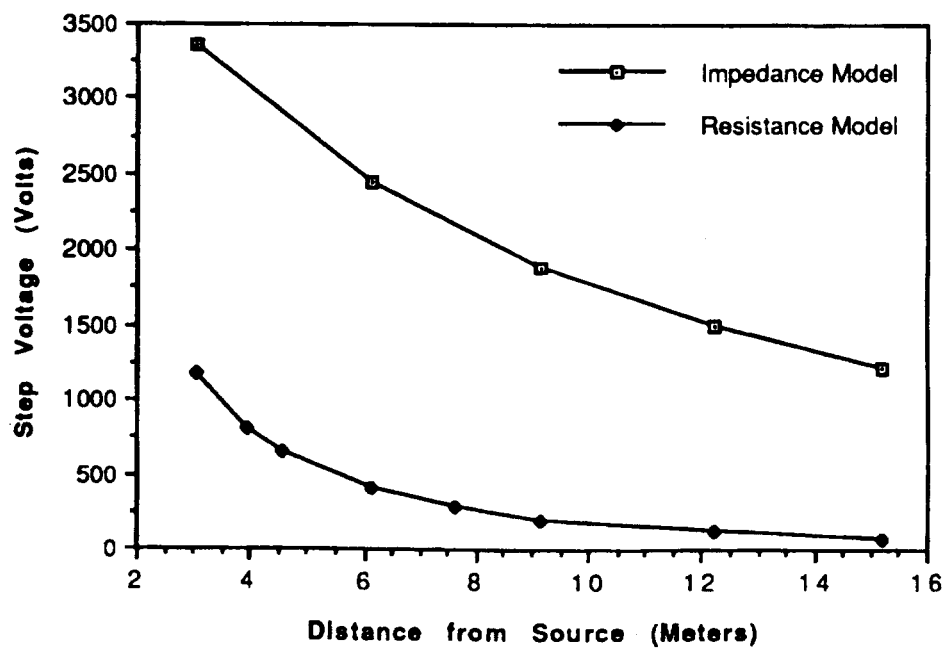


Figure 4. Comparison of the Impedance Model and the Resistor (DC) Model for $\rho_s = 100 \Omega \cdot m$.

Table I. Step Voltages by Catenary Wire Current Injections
(‘Full Impedance Model’ with $\rho_w = 20\Omega \cdot m$).

Source Distance		Step Voltages (volts)	
xft (feet)	z (meters)	$\rho_s = 1500\Omega \cdot m$	$\rho_s = 100\Omega \cdot m$
10	3.05	4245	3355
20	6.10	3740	2453
30	9.15	3370	1886
40	12.2	3047	1494
50	15.2	2714	1209
60	18.3	2401	995
70	21.3	2136	829
80	24.4	1909	698
90	27.4	1713	594
100	30.5	1527	509
110	33.5	1361	439
120	36.6	1205	382
130	39.6	1070	334
140	42.7	969	293
150	45.7	857	259

Table II. Step Voltages by Catenary and Vent Tower Wire Current Injections
for $\rho_s = 1500$ and $100\Omega \cdot m$ (Both with $\rho_w = 20\Omega \cdot m$)

Work Area	Current Injection Scenarios	Step Voltage (Volts)	Step Voltage (Volts)
		$\rho_s = 1500\Omega \cdot m$	$\rho_s = 100\Omega \cdot m$
Southeast Corner	Oxidizer Vent	998	320
	CW #4	209	35.3
Northwest Corner	Fuel Vent	1214	417
	CW #9	169	29.1